Appendix 2

APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 4 28 JANUARY 2002

Relaxed SiGe-on-insulator substrates without thick SiGe buffer layers

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(Received 25 September 2001; accepted for publication 13 November 2001)

We have developed a technology for relaxing top SiGe layers with low dislocation density on Si substrates, without using thick SiGe buffer structures. By introducing a thin strained SiGe layer and the internal-oxidation (ITOX) process following the separation-by-implanted-oxygen (SIMOX) process, we have experimentally demonstrated relaxed SiGe-on-insulator (SGOI) substrates with the Ge content of 20%, and it has been realized that their dislocation density is a factor of 20 lower than that of SGOI with SiGe buffer layer. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1435799]

Strained-Si metal-oxide-silicon field-effect-transistors (MOSFETs) are one of the most promising device structures for high-speed sub-100-nm complementary-metal-oxide-silicon (CMOS).[1] Furthermore, we have recently proposed fully depleted strained-Si-on-insulator (SOI) MOSFETs fabricated on relaxed SiGe-on-insulator (SGOI) films.[2] To form a strained-Si channel on relaxed SiGe layer, a thick SiGe buffer layer has been a key technology for the lattice relaxation of the top SiGe layer.[1] By combining this thick SiGe buffer structure with the separation-by-implanted-oxygen (SIMOX) technology, we have succeeded that strained-SOI n- and p-MOSFETs with the enhancement of electron (60%) and hole (30%) mobility have been demonstrated,[2] using this SGOI substrate. In order to further improve the device performance, the increase in the Ge content of SGOI and much thinner SGOI films are mandatory. However, there are mainly two problems to realize such SGOI substrates.

Problem 1: The large drain leak currents are attributable to the dislocations in the top SiGe layer.[3] The dislocations of SGOI substrate are still induced by high density dislocations of the SiGe buffer structure.[3] Therefore, it is necessary to develop a new technology for realizing relaxed SGOI layers compatible with low dislocation density.

Problem 2: The melting point of SiGe layers with high Ge content is too low for high temperature annealing in the SIMOX process.[3,4] Since the lower limit for SIMOX annealing temperature is around 1320 °C, the Ge content is also limited to be lower than 14%.[4]

In this work, we propose a technology for high-quality relaxed SGOI substrates without using thick SiGe buffer layers. There are mainly three key points in this process. The first point is the direct growth of the strained-SiGe layer on Si substrate, without using thick SiGe buffer layers. The second point is the SIMOX process for forming buried oxide and relaxing the compressive stress of this strained-SiGe layer. The first and the second key technologies lead to avoid problem-1. The third is the low temperature internal-thermal-oxidation (ITOX)[5] technology for thinning a SGOI film and increasing its Ge content by thinning SGOI substrates,[6] to overcome the problem-2.

Figure 1 shows the process for relaxed SGOI structures with higher Ge content. As shown in Fig. 1(1), a 300-nm-thick strained $Si_{0.9}Ge_{0.1}$ film was formed directly on a Si substrate without thick graded SiGe buffer structures. This thickness should be much thinner than the critical thickness of SiGe on Si [7] at growth temperature of the SiGe epitaxy, in order to suppress the dislocation generation in this SiGe layer. Next, as shown in Fig. 1(2), the SIMOX process (oxygen ions dose of 4×10^{17} cm^{-2}) was carried out to form the buried oxide between the top SiGe and the Si substrate, leading to the relaxation of the strained SiGe layer through a slip between the top SiGe and the buried oxide layers. The sufficiently low Ge content allows using the SIMOX annealing at high temperature of 1335 °C, which is necessary to form a continuous buried oxide layer. Subsequently, SGOI was thinned by low temperature ITOX process[6] (annealing in Ar–O_2 mixture gas) to increase the Ge content, as indicated in Fig. 1(3). Here, this annealing temperature of 1200 °C should be lower than the melting point of SiGe layer with increased Ge content. When SiGe layers are oxidized, Ge atoms are rejected from the oxide. On the other hand, the diffusion of the Ge atoms toward substrates is blocked by buried oxide layer, resulting in condensing into the remaining SGOI layers.[7]

In order to evaluate the dislocation density, the SiGe surfaces are etched by the acid solution, and the number of the etched pits are counted. Figure 2 shows the scanning electron microscopy (SEM) observation of etched SiGe surface (a) before and (b) after the SIMOX process. Moreover, Fig. 2(b) indicates the SEM photos of SGOI substrates (1) with and (2) without SiGe buffer layer. It is found [Fig. 2(b)] that the dislocation density without SiGe buffer layer whose thickness is 0.8 μm can be reduced by about 1/20, compared to SGOI with a thick and relaxed SiGe buffer layer. Figures 2(a) and (b)-(1) also show that the dislocation density of the SGOI substrate after the SIMOX process are about one third of that of bulk SiGe before the SIMOX process, suggesting that the dislocation density of SiGe layer can also be reduced by high temperature SIMOX annealing. Therefore, the SGOI without SiGe buffer structure has a much higher quality, compared to the bulk relaxed-SiGe substrate with SiGe buffer layer, because the former dislocation density is lower than the latter by about two orders of magnitude.

Figure 3 shows the transmission-electron-microscopy

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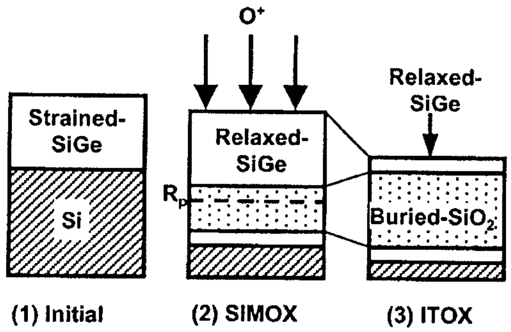

FIG. 1. Fabrication steps for relaxed-SGOI substrate. (1) 300-nm-thick strained-$Si_{0.9}Ge_{0.1}$ without thick SiGe buffer layer is grown directly on a (100) Si substrate, using an ultra-high-vacuum (UHV) chemical-vapor-deposition (CVD) reactor. (2) Next, oxygen ions with the dose of 4×10^{17} cm^{-3} at 180 keV are implanted into the Si substrate. R_p shows the projected range of oxygen ions. High temperature (1335 °C) annealing is carried out for 6 h to grow a buried SiO_2 layer inside the Si substrate. (3) Low temperature (1200 °C) ITOX annealing is carried out in Ar–O_2 mixture gas to thin the SiGe layer on the buried oxide and to increase its Ge content as well as to enhance the buried oxide thickness.

(TEM) photographs of the cross section of the SGOI substrates after (a) SIMOX and (b) ITOX processes. It is confirmed that the buried oxide is uniformly fabricated by the SIMOX process. After the ITOX process, the SiGe thickness on the buried oxide is thinned to 40 nm from 300 nm, which is effective in suppressing short channel effects of MOSFETs. It is also observed that the buried oxide thickness increases from 80 to 110 nm. Thus, the improvement in the breakdown voltage of the buried oxide is expected in this SGOI substrate after the ITOX process. On the other hand, the Ge content and the stress of the SGOI substrate are evaluated by the Auger electron spectroscopy and the Raman spectroscopy, respectively. Figure 4 shows the relaxation rate (solid line) and the Ge content (dashed line) of surface SiGe layer before and after the SIMOX process, and after the ITOX process. The relaxation rate is defined by $(\Delta\omega-\Delta\omega_{\mathrm{strain}})/(\Delta\omega_{\mathrm{relax}}-\Delta\omega_{\mathrm{strain}})$, where $\Delta\omega\pi$is the measured Raman shift, $\Delta\omega_{\mathrm{strain}}$ and $\Delta\omega_{\mathrm{relax}}$ are the calculated Raman shifts of fully strained and relaxed SiGe layers,[8] respectively. It is demonstrated that the fully strained-SiGe layer can be fully relaxed after the SIMOX process. In addition, even after the low temperature ITOX process, the SGOI substrate is almost fully relaxed (93%). Therefore, the relaxation mechanism of the SGOI substrate is ascribed to a large slip between the top SiGe layer and the buried oxide at high temperature.

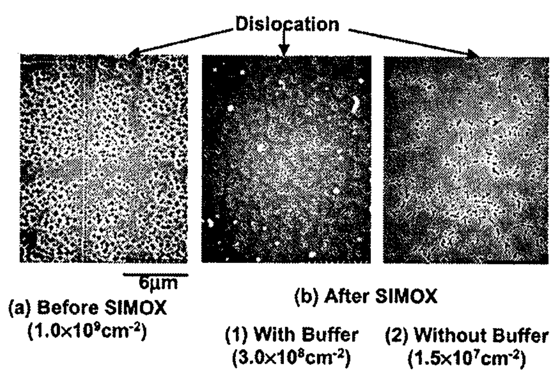

FIG. 2. SEM observation of dislocations in top SiGe layer etched by acid solution, (a) before and (b) after the SIMOX process. In addition, 2(b)-(1) and (2) show the dislocation density of SGOI with and without SiGe buffer layer, respectively. The graded SiGe buffer layer of (a) and (b)-(1) conditions is 0.8 μm thick; (b) indicates that the dislocation density of SGOI without SiGe buffer layer can be reduced by about 1/20.

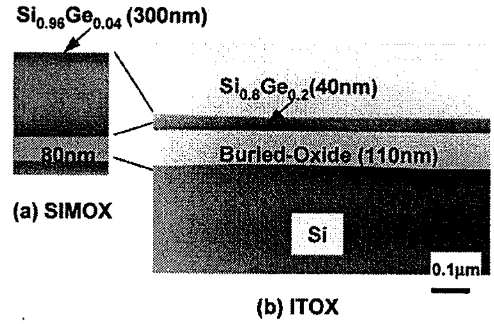

FIG. 3. TEM photographs of the cross section of SGOI substrate after (a) SIMOX and (b) ITOX processes. In both cases, the buried oxide layer was uniformly formed. After the ITOX process, the SiGe thickness on the buried oxide can be thinned to 40 nm from 300 nm of (a) SIMOX process, and in addition, the buried oxide thickness increases from 80 to 110 nm.

The Ge content after the SIMOX process becomes about one third of the strained-SiGe layer, because Ge atoms diffuse toward the Si substrate during the high temperature annealing process. However, the ITOX process demonstrates that Ge atoms are condensed to 20% from 3.6%, because Ge atoms are rejected from the oxide layer into the remaining SiGe layer during thinning process due to oxidation.[7] These results mean enable the combination of SIMOX and ITOX processes to obtain SGOI with the Ge content higher than in the initial strained SiGe layer.

In conclusion, we have developed the technology for relaxing top SiGe layers, without using thick SiGe buffer layers. By introducing a thin strained SiGe layer and the ITOX process following the SIMOX process, relaxed SGOI substrates with the Ge content of 20% and the dislocation density of one order of magnitude lower than in previous ones have been realized. This SGOI substrate is applicable to high-speed strained-SOI MOSFETs under sub-100-nm regime.

The authors would like to thank A. Kurobe for his continuous support of this work.

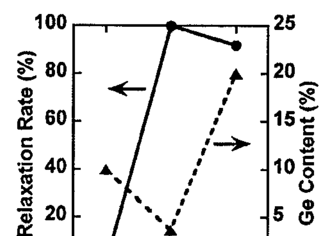

FIG. 4. Relaxation rate and Ge content of surface SiGe layer before [initial condition shown in Fig. 1-(1)] and after the SIMOX process [Fig. 1-(2)], and after ITOX process [Fig. 1-(3)]. The relaxation rate and the Ge content are obtained by Raman shift and Auger electron spectroscopy analysis, respectively. The strained-SiGe layer can be fully relaxed after the SIMOX process, and even after the low temperature ITOX process, thinned SGOI substrate is almost fully relaxed (93%). The Ge content after the SIMOX process becomes about one third of strained-SiGe layer. However, ITOX process demonstrates that Ge atoms are condensed to 20% from 3.6%.

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